

Detection of invariants in probabilistic relations between events by means of exploratory behaviors

(Detección de invariantes en relaciones probabilísticas entre eventos mediante conductas exploratorias)

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Abstract

Research has demonstrated that individuals are sensitive to contingent probabilistic relations between events in the environment. However, the factors that underlie this adaptation are not fully understood. Thus, the aim of this study was to assess whether repetitions and variations in participants' responses contributed to the detection of invariance in probabilistic environments. In Experiment 1, participants were exposed to relations between the initial and final trajectories of an arrow under probabilities of 1.0, 0.9 and 0.8. In the first half of the session, the arrows followed predominantly straight trajectories, but in the second half they changed to broken ones, or *vice versa*. In Experiment 2, sessions began with no relation between the arrows' initial and final trajectories ($p= 0.5$), but in the second half probabilities of 1.0, 0.9 and 0.8 were presented for straight or broken trajectories. In both experiments, as the relation between the arrow's initial and final trajectories became more changeable, variations of behavior increased, while under more constant relations repetitions increased. Results support the notion that adaptation to probabilistic relations between events entails exploratory behaviors performed to detect invariant information of the environment.

Keywords: Invariants, Contingency, Probability of Continuity, Information, Exploratory Behaviors

Resumen

La investigación ha mostrado que los individuos son sensibles a las relaciones probabilísticas contingentes entre los eventos del ambiente. Sin embargo, los factores que subyacen a ésta adaptación no son completamente claros. El objetivo del este estudio fue analizar si las repeticiones y variaciones de las respuestas de los participantes contribuían a la detección de invariantes en ambientes probabilísticos. En el Experimento 1, los participantes fueron expuestos a relaciones entre las trayectorias inicial y final de una flecha con probabilidades de 1.0, 0.9 y 0.8. En la primera mitad de la sesión, las flechas siguieron trayectorias predominantemente rectas y en la segunda mitad cambiaron a trayectorias quebradas, o *viceversa*. En el Experimento 2, se comenzó con la ausencia de relación entre las trayectorias inicial y final ($p= 0.5$) y en la segunda mitad de la sesión se presentaron las probabilidades 1.0, 0.9 y 0.8 para las trayectorias rectas y quebradas. En ambos experimentos se observó que conforme la relación entre las trayectorias inicial y final de la flecha era más cambiante, aumentaron las variaciones de la conducta, mientras que en las relaciones más constantes aumentaron las repeticiones. Los resultados apoyan la idea que la adaptación a las relaciones probabilísticas entre eventos implica conductas exploratorias realizadas para detectar la información invariante del ambiente.

Palabras clave: Invariantes, Contingencia, Probabilidad de Continuidad, Información, Conductas Exploratorias

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Introduction

Since Tolman and Brunswik's (1935) pioneering work, studies on the probabilistic character of the environment have provided insight into some properties of behavior. Wasserman and colleagues (Wasserman, 1990; Wasserman et al., 1993; Wasserman & Neunaber, 1986; Wasserman & Shaklee, 1984), for instance, conducted several experiments to evaluate whether humans are sensitive to conditional response-outcome relations. Their work was based on the assumption that the causal texture of the environment supports adaptive behaviors in a cause-effect relation (e.g. Killeen, 1981) in which consequences are contingent on the presence (positive contingency) or absence (negative contingency) of responses. A contingency implies a difference between, on the one hand, the probability of an event y (an outcome) given the occurrence of another event x (a response) [$P(y|x)$], and, on the other, the probability of an event y given the non-occurrence of another event x [$P(y|\neg x)$]. Therefore, contingency involves $\Delta P = P(y|x) - P(y|\neg x)$. The first condition indicates a positive relation between events, while the second points to a negative one. Wasserman and cols. varied the relations between response and consequence probabilistically using probability values distributed between 1.0 and -1.0, passing through 0.0. These values indicated, respectively, a positive or negative contingency, or the absence of any contingency. Those authors found that participants were consistently sensitive to judging probabilistic response-outcome relations. Their findings led to the conclusion that humans are quite capable of judging the causal texture of the environment (Katagiri et al., 2007).

Sensitivity to probabilistic relations in environmental events has also been reported in non-human animals. Stahlman, Blaisdell and colleagues (Stahlman & Blaisdell, 2011a, 2011b; Stahlman et al., 2010) were interested in the phenomenon of increased behavioral variability under conditions of low probability of reward (Antonitis, 1951; Gharib et al., 2001). Authors exposed pigeons and rats to different discriminative cues associated with distinct probability values, ranked from low-to-high. They used circular discs of different colors projected on a monitor and blocks of wood placed on an open field as discriminative cues for pigeons and rats, respectively. Their work demonstrated that the behavioral variation, measured as the spatiotemporal variation of pecking behavior in pigeons, and variation of searching behavior in rats, was modulated by the cue-signaled probability of reward, but in an inverse relation; that is, as the probability of the signaled reward increased, behavioral variation decreased. Conversely, as the probability of reward decreased, behavioral variation increased. Those authors argued that the expectation of reward was determinant in behavioral variation, since low and high expectations of reward increased and reduced variability, respectively. In adaptive terms, the expectation of reward is linked to how informative the environment is,

and it modulates behavior variation in the exploration and exploitation of food patches.

Apparently, the underlying factors that contribute to individuals' adaptation to probabilistic environments are not fully understood. In this regard, existing studies show some discrepancies with respect to their theoretical interpretation of their findings related to adaptive behavior to contingencies. While some studies, for instance, emphasize the role of strength in the association between events for detecting a response-outcome contingency (e.g. Katagiri et al., 2007), others focus on the importance of the cue-signaled reward expectancy for modulating adaptive behavior (e.g. Stahlman & Blaisdell, 2011a, 2011b). The role of strength in the association between events (e.g. response-outcome), however, has been questioned (Baum, 2012), leading to suggestions for novel approaches to explain the transaction among organism, behavior, and environment, without appealing to any strengthening of the response-reward association (Cowie, 2019).

An alternative way to understand contingency—or the probabilistic relation between two events—consists in assuming that organisms cope with probabilistic relations by detecting the invariants in the relationship between the two events (Covarrubias et al., 2017). In Gibson's ecological theory of perception, the concept of detection of invariants is of central importance in explaining, in general, how organisms perceive and behave in the environment (Gibson, 1967, 1966) and, specifically, in the context of probabilistic environments where both humans and non-human animals pick up the invariance of stimulus combinations such as relations between events (i.e., Pavlovian procedures) or response-outcome relations (i.e., instrumental and operant procedures; Gibson, 1966).

Detecting invariance entails that an organism actively explores the environment (Gibson, 1966) to perceive the "*relational properties* that remain unchanging despite change" in stimulation (Costall et al., 2003, p. 47, emphasis added). The information that guides perception and behavior resides, precisely, in these invariant relational properties of the environment (Gibson, 1967). Thus, the degree of invariance in probabilistic relationships will determine subjects' exploration, since exploratory behaviors are directed towards seeking invariant information in the environment (Gibson, 1966).

With this in mind, we designed an experimental situation that manipulated three probabilities of two reversed relations between events in order to evaluate whether subjects detected the invariance in these relations by means of behavioral patterns that entail exploration. Thus, under certain conditions with a probability of 1.0, subjects were exposed to a condition in which the relation between the initial position of an arrow's trajectory was invariant with respect to its final position. In other conditions, the probability of the relation between the arrows' trajectories was less invariant (i.e., $p = 0.9$ or $p = 0.8$). With respect to the reversing relations, some subjects responded in phase I of

the experimental session to predominantly straight arrow trajectories, but at the midpoint of the session (phase II) the relation was reversed so subjects had to respond to predominantly broken trajectories. Other subjects had to detect the change by responding to broken followed by straight trajectories.

The aim of this study was to assess participants' searching for invariants in reversed relations between the initial and final positions of an arrow's trajectory (straight-broken; broken-straight) maintained under three probabilities ($p=1.0, 0.9$ and 0.8). This approach reflects the assumption that probabilistic relations between arrows' trajectories determine how individuals explore their environment. Since the aim of exploratory behaviors is to detect invariance in the environment (Gibson, 1966), we hypothesized that when seeking to detect the invariance between the initial and final position of the arrow's trajectory under more changing probabilistic relations, participants will show a higher number of exploratory behaviors, while in the opposite case—that is, as probabilistic relations become more constant—these behaviors would decrease.

Experiment 1

Participants

A total of 35 undergraduate students (20 women, 15 men) aged 18-25 (mean= 19.23, SD= 1.85) participated voluntarily. They all read and signed a written consent form to participate in the study. Subjects were tested simultaneously in pairs in a single session.

Apparatus

The interface developed to test participants was installed in two computers (Toshiba, HP) equipped with Windows® 10. The experiment was conducted in a room 3.8 m in length, 3.5 m wide and 3.8 m high. An opaque screen (3M) measuring 2.14 m wide by 2.14 m high was placed in the middle of the room to prevent subjects from observing each other's performance.

Procedure

The interface presented dark blue arrows on a computer screen that moved from left-to-right against a light gray background along straight horizontal trajectories. Each successive trial began by presenting two arrows on the left side of the screen, aligned vertically and separated by 4 cm. The arrows moved horizontally at a velocity of 0.32 cm per second and crossed a dark gray, vertical, 5.15 cm wide bar, located on the center of the screen. When they passed through the vertical gray bar during their left-to-right movement, their trajectory was occluded from the participant's sight. On the right side of the screen, a vertical, black, 0.26 cm wide line was placed 8.28 cm from the right edge of the

centered, dark gray vertical bar. Participants had to click on that line to predict the destination of the arrow. Two blue rectangles, 1.32 cm high and 0.5 cm wide, were placed on that line and aligned to show the arrow's two possible destinations. The rectangles were aligned with the points of origin where the arrows began their movement.

Upon entering the room, participants were directed to take a seat in front of one of the two computers that were separated by a screen. The following instructions were then read to each subject before beginning the session (translated from Spanish):

We're going to show you a task that consists in following the movement of arrows. The arrows will move from left-to-right across the screen, disappear behind the bar, and re-appear on the other side. On the right side of the screen there is a black line with two rectangles. You have to choose the rectangle where you think the arrow will land.

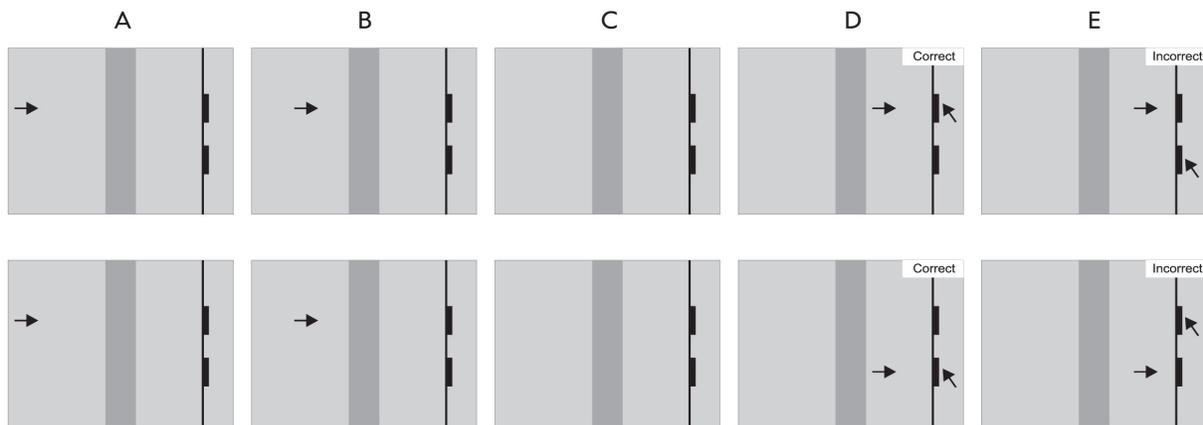
Figure 1 shows an example (left-to-right) of the interface that subjects observed on the computer screen during the task. One arrow was located at the top of the screen, the other at the bottom (panels A). Each trial began indistinctly with one of the two arrows, which flashed for two seconds on the left side of the screen before initiating its movement. The flashing signaled the beginning of the trial and the arrow that was about to move. The flashing arrow then moved from left-to-right (panels B) until it disappeared upon reaching the central vertical bar (panels C). It did not resume its movement until the subject clicked on one of the two target rectangles. At that point, it reappeared and continued its trajectory towards the right side of the screen, where it hit one of the targets (panels D, E).

The movement of each arrow was programmed according to the probability that, after crossing the bar, it would reappear on the straight or broken trajectory with respect to its starting point (Figure 1, top and bottom panels, respectively). The probability of 1.0 indicated that the location of the initial trajectory was invariant with respect to the destination; that is, under the straight trajectory condition, the arrow either began and ended its path in the upper or lower area of the screen. In the case of the broken trajectory, the arrow initiated its movement in the upper area of the screen, but after being concealed by the bar, reappeared in the lower area, or *vice versa*.

The probability of the arrow reappearing along the straight or broken trajectory was also of interest and therefore programmed, but with values of 0.9 and 0.8, such that if the straight trajectory was programmed at a probability of 0.9, 90% of the arrows followed a straight motion and 10% followed a broken path, in random order. In contrast, if the arrow's trajectory was broken, then on 90% of trials the trajectory would follow a broken path and on 10% of trials, a straight motion. The probability of 0.8 was programmed using the same rationale.

Figure 1

Representation of the movement of one of two possible arrows on the task. After appearing on the left side of the screen (A), the arrow moved from left-to-right (B), but disappeared upon reaching the vertical bar (C). It reappeared only after a response was emitted indicating one of the two targets. 'Correct' (D) or 'Incorrect' (E) feedback was then provided. The upper and lower panels correspond to the straight and broken trajectories, respectively.



The experimental session was divided into two phases, each one made up of 60 trials. In phase I (trials 1-60), the arrows followed one trajectory, but in phase II (trials 61-120) the path changed. Hence, if the trajectory programmed for trials 1-60 was straight, then for trials 61-120 it would change to broken, so that the arrow's trajectory was reversed in the middle of the experimental session, but without providing any informative signal. The programmed probability ($p= 1.0, 0.9$ or 0.8), in contrast, was maintained across the two phases. Since the subjects were kept unaware of the probabilities, trajectories, and moment of change, they had to detect them based on the outcomes.

The program provided feedback on the participant's performance after each trial. When the response coincided with the arrow's destination, the word 'Correct' appeared in green in the upper right corner of the screen (Figure 1, panels D); if it did not, then the word 'Incorrect' was shown in red (Figure 1, panels E).

Participants were assigned randomly to one of 6 groups, as shown in Table 1. Those in groups 1 ($n= 6$) and 2 ($n= 6$) were exposed to the probability of 1.0; those in groups 3 ($n= 5$) and 4 ($n= 6$) were exposed to the probability of 0.9; and those in groups 5 ($n= 6$) and 6 ($n= 6$) to the probability of 0.8. Participants in the odd-numbered

Table 1

Design of Experiment 1

Groups	Phase I		Phase II	
	Probability	Trajectory	Probability	Trajectory
1	1.0	Straight	1.0	Broken
2	1.0	Broken	1.0	Straight
3	0.9	Straight	0.9	Broken
4	0.9	Broken	0.9	Straight
5	0.8	Straight	0.8	Broken
6	0.8	Broken	0.8	Straight

groups were exposed initially to predominantly straight trajectories, followed by broken paths, while those in the even-numbered groups were exposed first to predominantly broken trajectories and then to straight paths.

Data analysis

Two dependent variables were reported: the proportion of hits (i.e., when the response coincides with the arrow's destination), and the proportion of the conditional probability of a hit for a repetition [$p(\text{hit}|\text{repetition})$] or variation [$p(\text{hit}|\text{variation})$] (described below). These dependent variables were calculated in blocks of 10 trials as the number of occurrences divided by 10. For both dependent variables, statistical analyses were conducted by a mixed-design 3×2 ANOVA (probability \times trajectory). The three levels of the between-subjects factor were the probabilities: 1.0, 0.9 and 0.8. The two levels of the within-subjects factor were the straight or broken path of the arrow. For each dependent variable (proportion of hits, proportion of conditional probabilities) an ANOVA was performed separately for each sequence: straight-broken and broken-straight.

Results

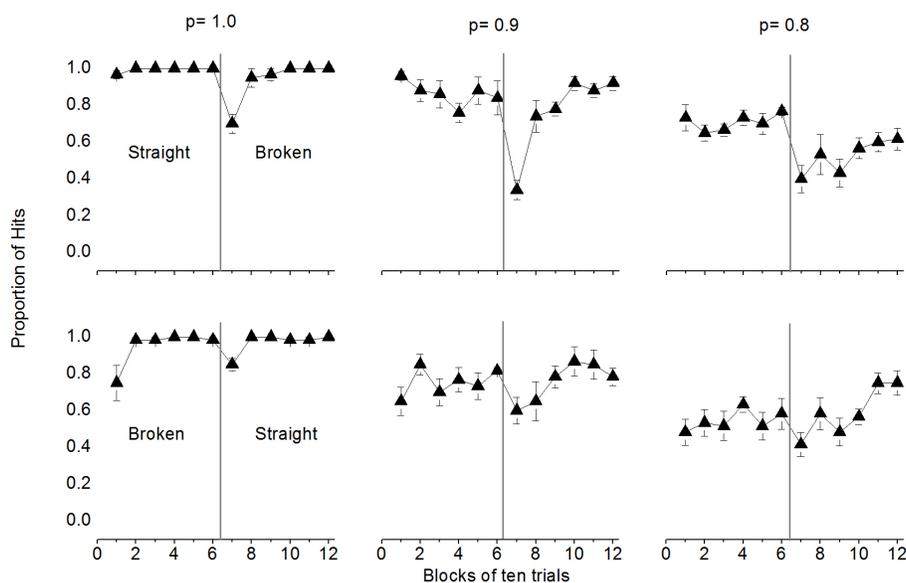
Figure 2 presents the means of the proportion of hits (a measure that evaluates whether participants are sensitive to the probabilistic relations between events) under

the probabilities of 1.0 (left panels), 0.9 (middle), and 0.8 (right). The top panels show the proportion of hits when the arrow followed the straight trajectory in the session's first 60 trials, before switching to the broken path for the final 60 trials. The bottom panels show the proportion of hits for the counterbalanced groups, where the arrow first followed the broken trajectory and then switched to the straight path for the final 60 trials. The vertical line across the panels indicates the transition trial when the arrow changed its trajectory from straight-to-broken (top panels) or broken-to-straight (bottom panels).

The three top panels in Figure 2 show that as the probability of the continuity of the arrow's trajectory was lowered, the proportion of hits decreased. The ANOVA detected a main effect of probability [$F(2,99) = 115.29, p < .001$]. Tukey's post hoc tests were applied, and results revealed significant differences between the probabilities of 1.0 and 0.9 ($p < .001$), 1.0 and 0.8 ($p < .001$), and 0.9 and 0.8 ($p < .001$). The top panels in Figure 2 also show that at the onset of phase II (broken trials), the proportion of hits decreased in the 10 trials following the trajectory change, before increasing progressively to values similar to those reported in phase I. The ANOVA detected these effects and revealed a significant main effect of the sequence of the trajectories [$F(1,99) = 25.30, p < .001$], but did not detect any interaction effect between probability and sequence [$F(2,99) = 2.79, p = .065$].

Figure 2

Means of the proportion of hits for the probabilities of 1.0 (left panels), 0.9 (middle), and 0.8 (right) under the straight-to-broken trajectories (upper panels), or vice versa (bottom panels). The error bars indicate standard errors of the mean.



The three bottom panels in Figure 2 correspond to the counterbalanced sequence (broken-straight) of the arrows' trajectories. Consistent with the top panels, the bottom ones show that the proportion of hits decreased with the lower probability of continuity in the motion pattern (straight or broken). The ANOVA detected a main effect of probability [$F(2, 105) = 86.78, p < .001$], while Tukey's post hoc test found differences between the three probabilities: 1.0 and 0.9 ($p < .001$), 1.0 and 0.8 ($p < .001$), and 0.9 and 0.8 ($p < .001$). Upon assessing whether performance on the broken trials (phase I) differed from that of the straight trials (phase II), the bottom panels in Figure 2 show that the proportion of hits first decreased after the trajectory change, but then increased to values similar to those from phase I. However, the changes after the switch were less noticeable than in the case of the straight-broken sequence (top panels). In accordance, the ANOVA failed to detect a main effect of the sequence of the trajectories [$F(1, 105) = 1.46, p = .229$] or any interaction effect between probability and sequence [$F(2, 105) = 0.45, p = .633$].

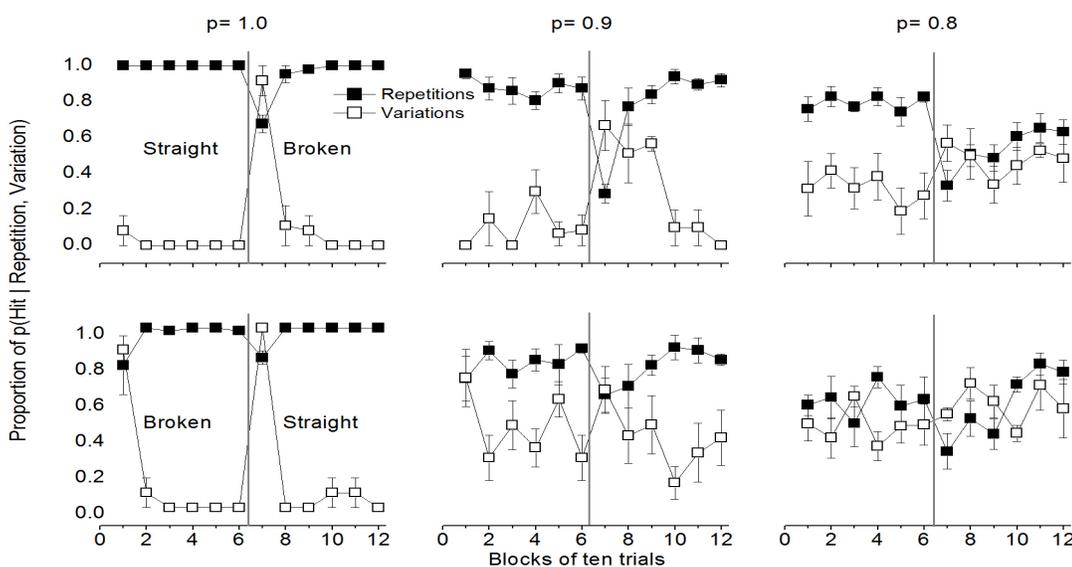
Since the relation between the arrows' trajectories changed more markedly at the lower probabilities, we evaluated whether subjects' performance became more variable when they had to detect the relations between events under lower probabilities and, conversely, if their performance became more repetitive at the higher probabilities. To determine this, our next analysis evaluated whether participants' performance corresponded to underlying in-

crements (variations) or decrements (repetitions) of exploratory behaviors. To this end, we measured those activities by recording the responses on the target position with respect to the arrow's original location. In this case, the target response could be located in the same, or opposite, direction to the arrow's origin. When two consecutive target responses indicated the same –or opposite– direction with respect to the origin point, a *repetition* was recorded. In contrast, if one target response indicated the same direction as the arrow's origin, but the subsequent one was aligned in the opposite direction (or *vice versa*), then a *variation* was recorded.

This analysis allowed us to represent the proportion of hits shown in Figure 2 in terms of repetitions and variations. We then calculated the conditional probability of a hit given that a subject emitted either a repetition [$p(\text{hit}|\text{repetition})$] or a variation [$p(\text{hit}|\text{variation})$] as a way to measure the exploratory activity that facilitated evaluating whether the feedback on the final arrow's trajectory guided subjects' seeking behavior. Reciprocally, by means of these exploratory behaviors, perceivers revealed the informative structure of the task. Figure 3 shows these behaviors under the straight-broken (top panels) and broken-straight (bottom panels) sequences. The three top panels in Figure 3 show that the lower probability of the continuity of the arrows' trajectories decreased the frequency of repetitions. As a result, the frequency of variations increased for both the straight (phase I) and broken (phase II) trajectories. The hi-

Figure 3

Means of the conditional probability of a hit for a repetition [$p(\text{hit}|\text{repetition})$] or variation [$p(\text{hit}|\text{variation})$]. Filled symbols represent repetitions, open symbols indicate variations. The probabilities and trajectories are arranged as in Figure 2. The error bars indicate standard errors of the mean.



ghest values for repetitions and the lowest values for variations were obtained with the probability of 1.0 (left panels), followed by 0.9 (middle), and 0.8 (right). For the case of repetitions, the ANOVA detected a significant main effect of probability [$F(2,99) = 71.32, p < .001$], while Tukey's post hoc tests for repetitions confirmed significant differences between the probabilities of 1.0 and 0.9 ($p < .001$), 1.0 and 0.8 ($p < .001$), and 0.9 and 0.8 ($p < .001$). For the case of variations, a significant main effect of probability was also detected [$F(2,99) = 24.11, p < .001$], and Tukey's post hoc test confirmed significant differences among the three probabilities: 1.0 and 0.9 ($p = 0.038$), 1.0 and 0.8 ($p < .001$), and 0.9 and 0.8 ($p < .001$). The top panels of Figure 3 also suggest an effect of the straight-broken sequence, as repetitions decreased and variations increased in block number 7, which included the 10 trials subsequent to the trajectory switch. After that, repetitions and variations returned to values close to those shown in phase I, except for the probability of 0.8, where repetitions and variations remained low and high, respectively. Consistent with these findings, the ANOVA revealed a significant main effect of the straight-broken sequence for both repetitions [$F(1,99) = 31.00, p < .001$] and variations [$F(1,99) = 21.75, p < .001$]. Variations did not show an interaction effect between probability and the sequence of the trajectories [$F(2,99) = 0.23, p = 0.791$]. Repetitions, in contrast, did show an interaction effect [$F(2,99) = 5.57, p = 0.005$] between probability and sequence.

Discussion

Our results show that the proportion of hits decreased as a function of reductions in the degree of task invariance, and that this effect was observed before (phase I) and after (phase II) the arrow trajectory was changed. In addition, they indicate that participants were more sensitive to the change in the arrow's trajectory under the straight-broken sequence than the broken-straight sequence, since in the first case the proportion of hits differed more greatly between phases I and II.

The analysis of the conditional probabilities of repetitions and variations suggests that these response patterns were strongly influenced by the probabilities of the arrow trajectories programmed by the task, as lower probability values engendered more variations and fewer repetitions. This suggests that in changing environments—those with less informative structures for guiding behavior—individuals actively seek the invariant information, which leads them to perform variations. However, under environments that are more constant, or have a more informative structure, behavior is more repetitive. Significantly, the results for conditional probability also suggest that the changes in the frequencies of repetitions and variations were guided by the feedback provided by the different probabilities of the continuity of the trajectories.

Another implication of these results is that the repetitions and variations emitted to detect the change in the arrow's trajectory were influenced not only by the probability of continuity, but also by the sequence in which the trajectories were presented. Thus, with probability set at 1.0, subjects accurately detected the reversal of the trajectory regardless of sequence (straight-broken or broken-straight), while under the probability of 0.9 they detected the change in the straight-broken sequence, but not in the opposite one. Finally, for the case of the probability of 0.8, participants barely detected the change when exposed to the straight-broken sequence and did not detect it at all in the broken-straight order.

In summary, these findings indicate that participants more accurately detected the reversal of the arrows' trajectory as the probability values of the spatial relations between trajectories (straight or broken) increased. It seems, then, that when the environment was more constant in phase I, the changes in phase II became more detectable. A possible explanation of this is that under the high regularity of phase I, a larger number of arrows reversed their trajectory in phase II. For instance, with the probability set at 1.0, all the arrows reversed their trajectories from straight-to-broken or broken-to-straight. This higher discrepancy of the arrow trajectories between phases I and II may have become more discriminable with the change of trajectory at the halfway point of the session. Conversely, the more changing the environment in phase I, the less discrepant the number of projected arrows in phase II and, consequently, the less detectable the trajectory change in mid-session. In other words, the adjustment to the reversed trajectories might result from the detection of the rearranged spatial layout after the reversal of the trajectory, so when the number of discrepancies in the number of arrows between the two phases of the task is higher, the detection of the change in the trajectories becomes more discriminable.

Experiment 2

In order to explore this hypothesis, we increased the degree of change in the second experiment by programming the probability of the continuity of the trajectory in phase I at 0.5. This meant that half of the arrows randomly followed one trajectory, and the other half the opposite path. In phase II, the participants in the six study groups were exposed to the probabilities of 1.0, 0.9 or 0.8. This manipulation allowed us to evaluate subjects' performance in an environment where no regularity could be detected in the first half of the session ($p = 0.5$), as well as their subsequent performance under the probabilities of 1.0, 0.9, and 0.8, which offered three levels of discrepancy from the probability of 0.5. With respect to the conditional probability analysis of repetitions and variations, we predicted that in the condition of the absence of environmental invariance ($p = 0.5$), repetitions and variations would show equal

proportions, since neither one could lead with certainty to obtaining 'correct' feedback. When the probability of the continuity of the trajectory shifted, we expected that individuals would detect that something in the task structure had changed and so, shift to variation in responses to reveal the invariant outcome that is informative of the new task structure, before settling into a new appropriate behavior. More specifically, with the probabilities set at 1.0, 0.9 and 0.8, we predicted that the repetitions and variations would differ more notably from those given with $p=0.5$, with higher discrepancies both between them and with respect to the straight trajectories.

Participants

Thirty-six undergraduate students (22 women, 14 men) aged 18-39 (mean= 20.17; SD= 4.01) participated voluntarily and signed their informed consent. All participants were tested in pairs in a single session.

Apparatus

The interface and room used in Experiment 2 were the same as those in Experiment 1.

Procedure

The task and instructions of Experiment 2 were the same as in Experiment 1, except that the probability programmed in phase I (trials 1-60) was 0.5 for all groups. At this probability, half of the arrows followed straight trajectories, and the other half followed broken trajectories, in random order. In phase II (trials 61-120), the probabilities of the continuity of the trajectory were programmed at 1.0, 0.9 or 0.8. The shift from phase I to II occurred at the mid-point of the session but was not signaled in any way (trial 61).

Participants were assigned randomly to six groups. Table 2 shows the six counterbalanced experimental groups arranged for Experiment 2. The participants in groups 1 ($n=6$) and 2 ($n=7$) were exposed to $p=0.5-1.0$, those in groups 3 ($n=6$) and 4 ($n=5$) experienced $p=0.5-0.9$, and the ones in groups 5 ($n=6$) and 6 ($n=6$) were exposed to $p=0.5-0.8$. At trial 61 of the session, the participants in the odd-numbered groups were exposed to predominantly straight trajectories, while the even-numbered groups were presented with predominantly broken trajectories.

Data analysis

As in Experiment 1, the proportion of hits and the conditional probability of a hit for a repetition [$p(\text{hit}|\text{repetition})$] or variation [$p(\text{hit}|\text{variation})$] were calculated in blocks of 10 trials. Since the interest in Experiment 2 was to assess whether performance under probabilities 1.0, 0.9, 0.8 differed more from that under $p=0.5$, with greater discrepancies between them, the dependent variables were evaluated under exposure to the probability of 0.5 and then compared to the subsequent probabilities of 1.0, 0.9 and 0.8 by means of t-tests. T-tests were performed in each one of the six groups given that, as in Experiment 1, each dependent variable was analyzed separately for each sequence: straight-broken and broken-straight.

Results

Figure 4 shows the proportion of hits. The left part of each panel represents participants' performance under the probability of 0.5, while the right section shows their performance under the probabilities of 1.0 (left panels), 0.9 (middle), and 0.8 (right) when the arrow followed straight (top panels) and broken (bottom) trajectories. The three top

Table 2
Design of Experiment 2.

Groups	Phase I		Phase II	
	Probability	Trajectory	Probability	Trajectory
1	0.5	Straight/Broken	1.0	Straight
2	0.5	Straight/Broken	1.0	Broken
3	0.5	Straight/Broken	0.9	Straight
4	0.5	Straight/Broken	0.9	Broken
5	0.5	Straight/Broken	0.8	Straight
6	0.5	Straight/Broken	0.8	Broken

panels of Figure 4 show that the proportion of hits with $p=0.5$ were close to chance (0.5), but that upon increasing the probability of the continuity of the trajectory in the second half of the session, the proportion of hits increased, with the probability of 1.0 generating the highest proportion, and 0.9 and 0.8 producing decreasing numbers of hits. t-tests revealed significant differences between exposure to the probability of 0.5 and the subsequent exposure to the probabilities of 1.0, $t(35) = -17.97$, $p < .001$, and 0.9, $t(35) = -5.79$, $p < .001$. However, the T-test found no difference in the proportion of hits between the probabilities of continuing trajectories of 0.5 and 0.8, $t(35) = -0.77$, $p = 0.44$. Consistent with the upper panels, the three bottom panels of Figure 4 show that with $p=0.5$ the proportions of hits were around 0.5, but that after the shift the proportion of hits increased for $p=1.0$, $t(41) = -8.32$, $p < .001$, and $p=0.9$, $t(29) = -5.24$, $p < .001$, though not for $p=0.8$, $t(35) = -0.18$, $p = 0.89$.

We also assessed whether these effects corresponded to underlying repetitions and variations. To this end, we evaluated whether exposure to the probability of 0.5 influenced the number of repetitions and variations under the subsequent probabilities of 1.0, 0.9 and 0.8, and whether the trajectory of the arrow influenced these behaviors.

Figure 5 shows the conditional probability of a hit given that participants performed both repetitions [$p(\text{hit}|\text{repetition})$] and variations [$p(\text{hit}|\text{variation})$]. The three top panels show that with the probability set at 0.5 (left part of the panels), repetitions and variations were distributed equally around the value of 0.5. However, after increasing the probability of the continuity of the straight trajectory (right part of the panels), repetitions increased and variations decreased, though only for the probabilities of 1.0 and 0.9. For the probability of 0.8, repetitions and variations showed values similar to those obtained with the probability of 0.5. The statistical analysis of repetitions revealed significant differences between $p=0.5$ and 1.0, $t(35) = -13.61$, $p < .001$, and between $p=0.5$ and 0.9, $t(35) = -6.05$, $p < .001$. However, the t-tests revealed non-significant differences between $p=0.5$ and 0.8, $t(35) = 0.21$, $p = 0.82$. For the case of variations, the t-tests revealed significant differences between the probability of 0.5 and 1.0, $t(35) = 7.87$, $p < .001$, and between $p=0.5$ and 0.9, $t(35) = 3.25$, $p = 0.003$, but not between $p=0.5$ and 0.8, $t(35) = 0.71$, $p = 0.47$.

The three bottom panels of Figure 5 show that under exposure to $p=0.5$, the conditional probabilities of repetitive and variable responses were distributed equally around the value of 0.5. However, upon increasing the probability

Figure 4

Means of the proportion of hits for the probability of 0.5 are shown in the left part of all panels, while the right part represents the means of hits for the probabilities of 1.0, 0.9 and 0.8 (left, middle and right panels, respectively). The error bars indicate standard errors of the mean.

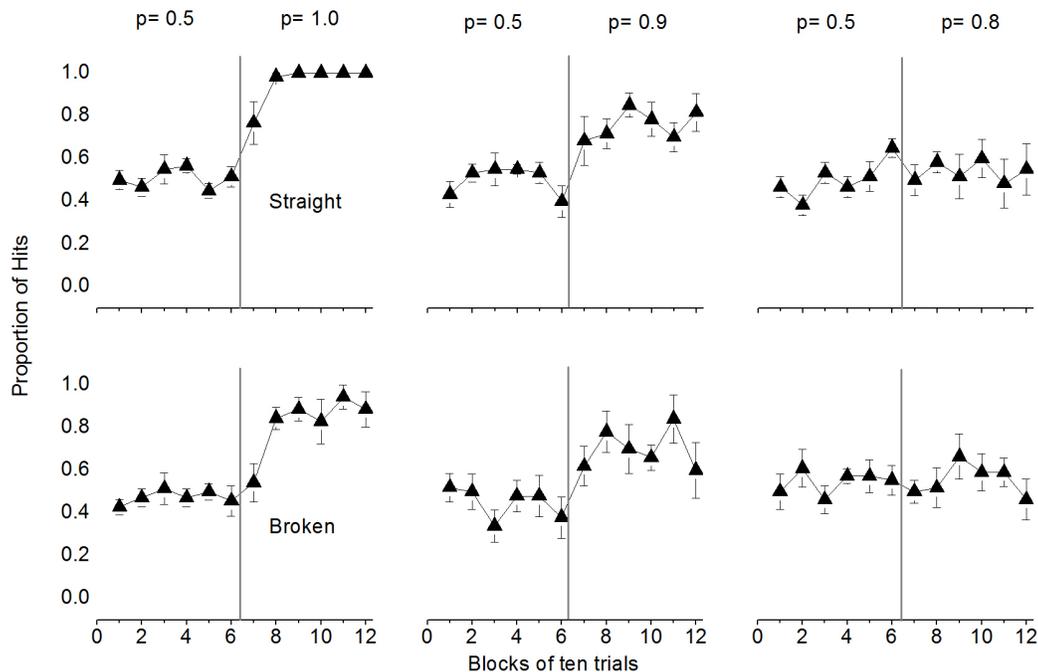
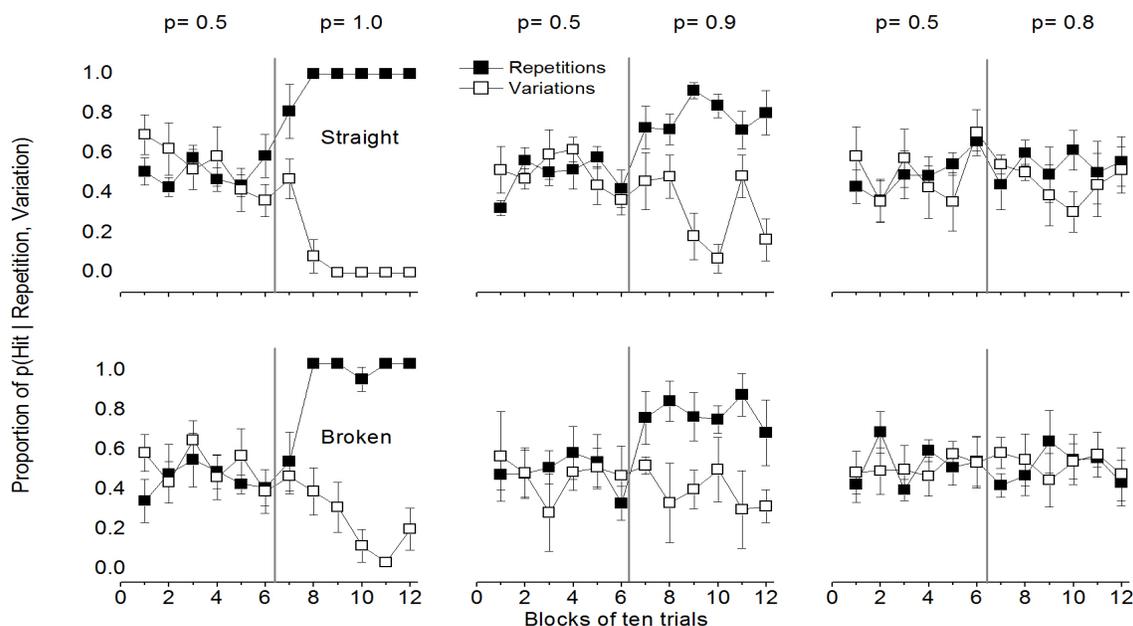


Figure 5

Means of the conditional probability of a hit for a repetition [$p(\text{hit}|\text{repetition})$] or variation [$p(\text{hit}|\text{variation})$]. The probabilities, trajectories and symbols are arranged as in Figure 4. The error bars indicate standard errors of the mean.



of the continuity of the broken trajectory, significant increments of repetitions were revealed for the probabilities of 1.0, $t(41) = -6.91$, $p < .001$, and 0.9, $t(29) = -5.69$, $p < .001$, but not for 0.8, $t(35) = 0.21$, $p = 0.828$. Regarding the variations after the shift, significant decrements were found for the probability of 1.0, $t(41) = 3.91$, $p < .001$, but not for those of 0.9, $t(29) = -0.85$, $p = 0.40$, or 0.8, $t(35) = -0.30$, $p = 0.75$.

Discussion

The results of Experiment 2 show that in phase I—with the probability of continuity of trajectories set at 0.5—hits, repetitions and variations were emitted at the level of chance. This suggests that no regularity was apparent or could be detected. In phase II, after exposure to the probability of 0.5, and regardless of the arrows' trajectories, the proportions of hits, repetitions and variations for the probabilities that generated the highest discrepancies ($p = 1.0$, and 0.9) differed more clearly from those for $p = 0.5$, though this did not occur when the probability was set at 0.8, which generated the lowest discrepancy. These results can be explained as follows: in phase I, participants repeated or varied their behaviors indistinctly since the consequences ('correct' or 'incorrect' feedback) were also obtained equally (and randomly). Under the probability of 0.5, therefore, the structure of the task was not informative for guiding behavior.

However, after the shift to phase II, with the probabilities set at 1.0 and 0.9, participants performed a brief exploration that resulted in greater variation, but quickly detected the new invariant in the feedback and they increased repetitions. These findings suggest that when discrepancies were the highest, participants detected the shift under both arrow trajectories, but that this did not occur under the conditions with the least discrepancy, as the repetitions and variations shown before the shift (with $p = 0.5$) were similar to those observed afterwards (with $p = 0.8$), indicating that the shift was not detected for either the straight or broken trajectories.

General discussion

The aim of this study was to assess whether exploratory behaviors contributed to the detection of invariants in reversed relational properties of probabilistic events using a task characterized by constant and changing spatial relations between the initial and final trajectories of a series of arrows. Our work demonstrates that the underlying factors that contribute to the individuals' adaptation to probabilistic environments may correspond to searching behaviors aimed to detect the invariance in the probabilistic structure of the task.

The results of Experiment 1 indicated that participants' hits decreased as the values of the probabilities in the

relationship between the initial and final positions of the arrow declined. These effects were observed both before and after reversing the arrow's trajectory but were clearer when subjects passed from the straight to the broken trajectory. These findings are consistent with those reported by Wasserman and colleagues, who showed that individuals adjusted their behavior to different response-outcome probabilities (Wasserman, 1990; Wasserman et al., 1993; Wasserman & Shaklee, 1984), and that this adjustment was also observed after reversing the response-outcome contingency (Katagiri et al., 2007). The results of Experiment 2 regarding the proportion of hits when the probability of occurrence of the same trajectory was close to chance (0.5) show that participants were also sensitive to exposure to the absence of invariance on the task ($p = 0.5$). This is consistent with Katagiri et al.'s (2007) study, which found that under a condition of non-contingency (i.e., the presence or absence of a response is followed equally by the outcome) individuals' performances approached the level of indifference.

When we analyzed participants' performance in terms of the conditional probabilities of repetitions and variations, the results of Experiment 1 suggested that these behavior patterns depended on the regularity of the task and were sensitive to its spatial characteristics. With respect to regularity, we found that variations increased, and repetitions decreased with decrements in the values of the probabilistic relations between the arrow's initial position and final destination. These results are consistent with studies that have reported that behavioral variability increases under conditions of low probability of reward (Antonitis, 1951; Gharib et al., 2001), and with studies showing that low probabilistic cue-reward relations induce greater variation in behavior, while lower variation is induced under high probabilistic cue-reward relations (Stahlman & Blaisdell, 2011a, 2011b; Stahlman, et al., 2010).

Our analysis of the repetitions and variations from phase I of Experiment 2 showed that these behavior patterns were also distributed around indifference; a result consistent with the fact that under this condition no regularity could be detected. In contrast, participants detected the shift (also in terms of the proportion of hits) when exposed to $p = 0.5$ and to conditions with the most discrepant probabilities ($p = 1.0$ and 0.9) but failed to detect it under the least discrepant condition ($p = 0.8$). Since these effects were consistent for both arrow trajectories, they support the notion that if the number of arrows projected in phase I of the experiment is more discrepant than in phase II, then discrimination of the shift will be higher.

Together, these results for the probability of regularity in the trajectories of the arrows support our assumption that at higher probabilistic relations between events—that is, as the contingencies of the task become more regular, and consequently more informative for guiding behavior—participants show more repetitions and fewer variations.

Conversely, as the task structure becomes less regular, and consequently less informative for guiding behavior—at lower probabilistic relations—behavior becomes more variable and less repetitive, highlighting the relevance of experience on the task. Therefore, our results suggest that through exploratory movements perceivers revealed the informative or invariant structure of the task. This is consistent with evidence that shows that individuals detect perceptually-relevant information by means of exploratory activities (de Paz et al., 2019; Mantel et al., 2015; McGuckian et al., 2019; Yu & Stoffregen, 2012), though our study differs in the sense that we evaluated the role of exploratory movements for detecting invariant information in probabilistic environments.

With regards to performance sensitivity to the spatial characteristics of the task, we found that the repetitions and variations emitted under different probabilistic relations also depended on the sequence in which the trajectories were reversed. Thus, under the highest probability ($p = 1.0$), the trajectory change was adequately detected in both reversal sequences (straight-broken, broken-straight), but when the probability was set at 0.9 , participants detected the change only in the straight-broken sequence. At the lowest probability ($p = 0.8$), the reversed trajectory was not detected in either sequence. These findings suggest that the detection of the reversal of trajectories was influenced by the probability of the continuity of the arrows' trajectories in interaction with their spatial characteristics (straight vs. broken).

Furthermore, the differential results dependent on the nature of the arrows' trajectories led us to ask how an object's straight or broken trajectory may influence its invariant detectability. Gibson (1966) argued that perceiving the motion of an object is no different from detecting invariants in a sequence of events: "the unbroken continuation of the optical motion is a consequence of the invariant laws of inertia and gravity in physics [...]. The invariant is implicit in the motion" (p. 280). With terrestrial environments arranged in such a way that bodies are displaced based on physical laws, an object like an arrow will move primarily through regular (straight), rather than irregular (broken) trajectories. These physical regularities found in natural environments are prior conditions that affect participants' performance in laboratory settings (Michotte, 1963), a finding that has also been obtained with non-human animals in conditioning settings. Cabrera et al. (2009), for example, found that pigeons showed more effectiveness in a Pavlovian conditioning procedure while tracking an image towards the source of food than when the image moved away from it. Hence, the effectiveness of conditioning was faster when the trajectory of the image and the food were aligned, not misaligned.

Taken together, the results of the two experiments reported herein support the assumption that individuals' behavior in probabilistic environments can be explained as the

search for invariant relational properties of the probabilistic structure of the task. These results also provide evidence to support the idea that sensitivity to contingencies in conditioning procedures can be seen as a case of detection of invariants (Covarrubias et al., 2017; Gibson, 1966). This alternative interpretation of contingency in conditioning studies may provide a framework for coherently integrating the results of ecological and behavior-analytic studies; an integration already suggested by some authors (Costall, 1984; Guerin, 1990; Morris, 2009; Tonneau, 2011).

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